

5. PRE-LAUNCH AND LAUNCH HAZARDS

5.1 INTRODUCTION

5.1.1 Background and Objectives

A hazard is the existence of any property or condition which, when activated, can cause injury, death, or result in damage to property. Of interest to this study are launch-related hazards which could affect third parties, namely people or property not connected with ELV operations. Thus, hazards which have effects contained within the boundaries of the Range are not discussed explicitly in this context.

A hazard potential exists because large quantities of liquid and/or solid propellants are part of the ELV and they could be unintentionally released in case of a launch accident. This hazard decreases with time into the flight because the quantities of on-board propellants decrease as they are consumed and the vehicle moves away from both the launch site and nearby populated areas. The exposure to launch accident hazards is greatest during the first few minutes after launch.

The major generic hazards in the event of an accident involving propellants during pre-launch and launch operations are:

1. Explosions: uncontrolled combustion of these propellants at a very fast rate per unit volume such that part of the chemical energy is converted to mechanical energy and part to heat. The mechanical energy is produced in the form of a blast wave with the potential of causing damage by crushing forces and winds (Sec. 5.2).
2. Debris: vehicle fragments that may land upon structures or populated areas. Fragments may include burning propellants which could explode or burn upon landing thus posing additional hazards of types 1 and 3 (Sec. 5.3).
3. Fires: uncontrolled combustion of the propellants at a slower rate than occurs in explosions, thus converting their chemical energy into heat only. The corresponding hazard is thermal radiation to people and property in the proximity of the fire (Sec. 5.4).
4. Toxic Vapor Clouds: some hypergolic propellants (such as monomethylhydrazine, nitrogen tetroxide and Aerozine-50) are toxic and corrosive. If released in an accident, unreacted vapors and aerosols may be transported by prevailing winds in the form of clouds. Hydrazine vapors are colorless and become white when combined with atmospheric moisture; nitrogen tetroxide vapors are reddish brown. Such clouds may pose a health hazard to people and are potentially harmful to animals and vegetation (Sec. 5.5). Other toxic propellants include fuming nitric acids, liquid

fluorine, anhydrous ammonia, nitromethane, ethylene oxide, chlorine trifluoride, chlorine, nitrogen trifluoride, hydrogen peroxide, hydrogen chloride and hydrogen cyanide.

Hazards associated with noise, sonic boom and small quantity releases of toxic materials are not considered in the same severity category as the hazards listed above and are not addressed in this report.

In a given accident, one or more of these hazards may occur and prevail in importance over the others, depending on the specific circumstances of the event such as: vehicle design, accident location, failure mode, propellant type, amount of propellant released, mode of release, environmental conditions and proximity of people and property. Sometimes, the occurrence of one hazard may preclude another because they compete for the same propellant. For example, when most of the propellant is consumed in a fire, a vapor cloud will not form. Other times, the hazards may be sequential -- such as the formation of toxic vapors in a fire or an explosion which may later pose a toxic vapor cloud hazard. The possible off-range impacts of launch accidents are illustrated in Sec.5.6.

This chapter presents a generic discussion of the major types of hazards associated with the ground preparation and launch of ELV's namely: explosions, debris, fires and vapor clouds. The objective is to provide an overview of the mechanisms involved in these hazards, the types of analyses used and the damage criteria. The hazards are considered to be of very low likelihood. Their applicability to, and magnitude in, any launch operation should be established by detailed analyses of the specific circumstances in each case. Such analyses for typical launch operations are discussed in Ch. 10, Vol. 3. A second objective is to provide a perspective on launch hazards by comparison with industrial and transportation accidents.

5.1.2 Major Information Resources on Rocket Propellant Hazards

In order to assess public risk exposure derived from launch hazards, information must be drawn from reports of major experimental and theoretical studies of the behavior of accidentally released propellants and fuels.^(1,3) These studies include test programs carried out by government agencies (NASA and DOD) where realistic accident scenarios were simulated on a large scale. Two notable test programs were projects PYRO⁽²⁾ and SOPHY.⁽³⁾ Both are summarized briefly below to illustrate the experimental basis for the information that follows in this chapter:

1. Project PYRO tested the explosive yield and flammability of liquid propellants namely:

- hypergolics (Aerozine-50 & Nitrogen Tetroxide used as fuel and oxidizer in both the Titan and Delta vehicles) in mass ratio of 2.25/1, in several configurations and with total weights of up to 200 to 1000 lb (90 to 450 kg);
- Liquid Oxygen/RP-1 (used in the Atlas vehicle) in mass ratio of 2.25/1 and with a total weight of up to 25,000 lb (11,000kg);
- Liquid Oxygen - Liquid Hydrogen (used in the Centaur vehicle) in mass ratio of 5/1 and in total weights of up to 100,000lb(45,000kg);
- Full-scale Saturn S-IV and a modified Titan I first stage.

Also, three accident conditions were simulated to produce different types of mixing effects:

- failure of an interior bulkhead separating fuel and oxidizer;
- fall back of a space vehicle on the launch pad with complete tank rupture and subsequent ignition;
- high velocity impact of a space vehicle after launch.

2. Project SOPHY addressed the hazards associated with handling, transporting, testing and launching of solid propellants. Solid propellants were tested in various geometries, sizes and weights (the latter varied from a few hundred to half a million pounds). Shock initiation was produced with a TNT charge centered on the end face of the propellant. Air blast and fire ball data were collected and analyzed statistically to develop scaling relationships. The critical charge diameter required to sustain a detonation in a typical composite propellant was determined to be between 60 and 72 inches.

These two test programs and their results were discussed extensively in a Chemical Propulsion Information Agency (CPIA) publication entitled "Hazards of Chemical Rockets and Propellants".⁽¹⁾ The results were analyzed to identify and quantify the resulting hazards and to develop methodologies for use in hazard analysis. Their findings are drawn upon extensively without having reviewed in detail the original reports of project PYRO and SOPHY.^(2,3) Other references of interest to such analyses are safety standards AFR 127-100⁽⁴⁾ and DOD 6055.9-STD.⁽⁵⁾

Against this background, we will present a generic discussion of the explosion, debris, fire and vapor cloud hazards associated with the accidental release of propellants. Hazard analyses of specific launch operations will also be discussed in Vol. 3, Chapters 9 and 10.

5.2 EXPLOSION HAZARDS

Explosion of an ELV can occur accidentally, as with the Titan 34D event in April, 1986, or as a result of a destruct command using the flight termination system. In some cases, flight termination is accomplished simply by shutting off the fuel supply to liquid fuel engines. In this case, an explosion may not occur unless the intact vehicle and its remaining fuel impact the ground sharply.

An explosion is a very rapid expansion of matter into a volume greater than its original volume. The cause of the expansion might be combustion, electrical discharge (such as lightning) or a purely mechanical process such as the bursting of a cylinder of compressed gas. The faster the energy is released, the more violent the explosion.

Rocket motors are designed to burn their fuels and release their energy in a controlled combustion process called a deflagration, or simply, a flame. In a deflagration the reaction front is driven by diffusion mechanisms. At steady state, it proceeds in the material at a rate lower than the speed of sound.

Under some conditions, the rate of energy release can increase significantly, leading to an explosion. The combustion process is then called a detonation.

In a detonation the reaction front consists of a shock wave followed by a flame. The reaction front is driven by a shock compression mechanism. At steady state, it proceeds in the material at a rate faster than the speed of sound.

There is a spectrum of reaction possibilities between steady state deflagrations and detonations, such as a fast deflagration and a weak detonation, with the potential of a transition from one reaction to another. The deflagration-to-detonation transition is referred to as DDT. A shock-to- detonation transition is also possible and is referred to as SDT.^(6,7)

For solid propellants (see Table 3-3, Vol. 1, Ch. 3), cross-linked double base hybrid materials (DOD Class/Division 1.1--old Class 7) were always considered in the past to represent a detonation hazard; most composite propellants (Class/Division 1.3--old Class 2) were considered to represent a fire (deflagration) hazard. However, recent trends in rocket motor design include: more energetic composite propellants, higher solid loading densities, larger grain diameters and greater mass. The net effect is that composite propellants may also detonate inadvertently under the dynamic conditions of accidents. Although, they may require a larger initiation energy than

Class/Division 1.1 propellants and their detonation may not be self-sustaining, resulting in lower yields⁽⁷⁾.

A number of conditions influence the likelihood of solid propellant detonation:^(6,7)

- propellant toughness;
- motor geometry, core configuration, diameter, length to diameter ratio, chamber pressure, case bonding technique and propellant residual strain;
- propellant critical diameter and geometry;
- propellant granular bed characteristics (pyrolysis and ignition) both thermally and mechanically induced, leading to faster combustion terminating in a detonation (DDT);
- propellant response to shock (SDT);
- propellant response to delayed reduced shock (referred to as XDT)
- impact velocity and surface impacted (water, sand or concrete).

A question of particular interest is whether activation of the destruct system is likely to detonate solid rocket boosters. This subject was studied recently by the Naval Surface Weapons Center (NSWC) for a filament wound graphite case material.⁽⁸⁾ They tested:

- linear shaped charge (LSC)/propellant case interactions;
- detonability and shock sensitivity;
- material response (breakage of propellant).

They concluded that activation of LSC would not detonate the Solid Rocket Booster propellant. At most, a rapid burn is expected.

For liquid propellants, the likelihood of detonation is influenced by chemical composition and conditions such as:

- degree of fuel and oxidizer mixing and size of the mixture prior to initiation;
- confinement of the products of combustion;
- presence of obstructions or flow instability that generate turbulence and result in increased reaction areas.

Such conditions are encountered in accidents to various degrees. Thus, it is usually very difficult to predict with certainty whether or not a detonation will occur.

Still, overpressure can result if the reaction is fast enough, even though it is not an ideal, steady state detonation. The

main difference is in the near-field where a detonation generates a much higher overpressure. This difference decreases further away from the center of the explosion. The far-field is of particular importance to this study which focuses on potential damage to the public (third parties) off-range. Overpressure estimation methods are presented in the next section.

5.2.1 Blast Waves

Scaling laws are used to calculate characteristic properties of blast waves from explosions. With the aid of such laws, it is possible to present characteristics of the blast wave, for any yield, in a simple form. This is presented below for the case of air at constant temperature and pressure.

Full-scale tests have shown that these relationships hold over a wide range of explosive weights (up to and including megatons). According to the scaling laws, if d_1 is the distance from a reference explosion of W_1 lb at which a specified hydrostatic overpressure or dynamic pressure is found, (Dynamic pressure $q = 1/2 \rho v^2$, where ρ is air density and v is particle velocity), then for any explosion of W lb, these same pressures will occur at a distance, d , given by:

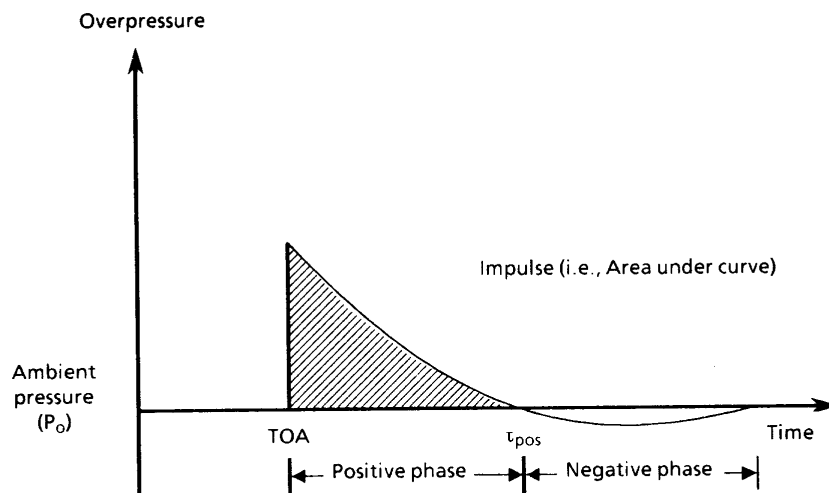
$$d/d_1 = (W/W_1)^{1/3} \quad (5-1)$$

In other words, the pressures are functions of a unique variable $(d/W^{1/3})$ called the scaled-distance or k-factor.

Cube-root scaling can also be applied to the arrival time of the shock front, positive-phase duration and impulse; the distances concerned are also scaled according to the cube-root law (see Figure 5-1 for a definition of these terms). The relationships may be expressed in the form: $t/t_1 = i/i_1 = d/d_1 = (W/W_1)^{1/3}$, where t represents arrival time or positive-phase duration, i is the impulse and the subscript 1 denotes the reference explosion W_1 .

These relationships are well established and accepted in the literature. They form the basis of most explosion models, including that used in Chapter 10 of this report.

It should be noted that the above relationships are for blast waves in free field, under ideal conditions. In a real, stratified atmosphere, shock focusing may occur producing higher overpressures than in free field. Such effects have been taken into account in a computer model named BLAST based on acoustic wave propagation. The model was developed by WSMC and has been verified experimentally.⁽⁹⁾



- (1) TOA (time-of-arrival) = The time required for the shock wave to transit the distance from the center of the explosion to the point at which the measurement is to be made.
- (2) P (overpressure) = Peak pressure above ambient conditions.
- (3) τ = Positive phase duration - the length of time (measured from the first pressure rise) necessary for the overpressure to return to the ambient pressure.
- (4) Positive phase impulse = $\int_0^{\tau} P(t) dt$

FIGURE 5-1. DEFINITION OF SHOCK WAVE PARAMETERS (Ref. 1)

5.2.2 TNT Equivalency Analysis

It is conventional to express the magnitude of an explosion of a given material (e.g., solid or liquid propellant) in terms of an equivalent weight of TNT (symmetrical tri-nitrotoluene, a conventional ordnance explosive) required to produce essentially the same blast wave parameters. The TNT equivalent weight was selected because of the large amount of experimental data available on blast waves and damage produced by TNT explosions. A given material may have several TNT equivalent weights depending on the selected blast wave parameter, i.e., it may have an equivalent weight based on peak overpressure, another based on positive impulse, (see Glossary, App. A, or Figure 5-1), etc. Peak overpressure is more commonly used, however, to define TNT equivalence. TNT yield refers to the TNT equivalent weight expressed as a percent of the weight of the propellant.

The TNT-equivalent analysis has a number of limitations that should be borne in mind to obtain valid comparisons. They are:

- Not all the accidentally-released material is involved in the explosion: part of it may disperse without reacting and part may react at a different time or location from the explosion. Accordingly, measured TNT yields of liquid propellants were found to depend on the degree of fuel/oxidizer mixing prior to explosion initiation. This degree of mixing depends, in turn, on the rate of mixing (a function of vehicle design, failure mode and accident conditions) and its duration (a function of when ignition occurs).
- Of the portion of released material that reacts in the explosion, part of it may detonate and part may deflagrate, with the latter contributing little energy to the blast. Predicting whether a detonation or deflagration (or any combination of them) will occur is a very complex subject, as discussed earlier. The outcome depends on the propellant properties and on the conditions of the accident. For example, with solid propellant fragments, an impact speed greater than 300 ft/sec is likely to have sufficient energy to initiate the detonation of that fragment upon impact.⁽⁷⁾
- Even for the portion of the released material that contributes directly to the blast energy, the blast characteristics are different from those of a TNT charge with an equivalent energy. Measured overpressure amplitudes are generally lower and durations are longer because of a slower reaction rate for propellants than for TNT. This rate depends on

accident-specific conditions such as: strength of initiating source, degree of confinement and shape of propellant.

Thus, the TNT yield of a material is not an absolute property such as density or molecular weight. Instead, it depends on the test conditions in which it is measured. Fortunately, the dependence of blast parameters on yield is low because of the cube-root exponent in the scaling law (Eq. 5-1). Hence, the prediction of a hazard distance (d) is not very sensitive to the employed yield (W). For example, if the yield is off by 50 percent, the distance (at which a particular overpressure is reached) is off by only 15 percent. Thus, the TNT method of analysis has been used effectively over many years despite the limitations mentioned above.

In 1978, NASA established an Explosive Equivalency Working Group to define potential failure scenarios which could lead to an explosion and to estimate the maximum credible explosive TNT equivalency for these explosions. The most complete documentation of the findings of this group is reportedly in a collection of briefing charts by W.A. Riehl et al.⁽¹⁰⁾ The work performed by this group provided a basis for many subsequent studies,⁽¹¹⁾ many of which have quoted verbatim TNT equivalent values from Ref. 10. This is illustrated in Table 5-1, which is extracted from a study on shuttle safety.⁽¹¹⁾ A variety of failure modes and accident scenarios are identified for the external tank and the solid rocket motors; a maximum credible explosive equivalent (or TNT yield) is estimated for each case. Also, the range for these maximum credible TNT yields varies from:

- 5 to 50% for LH₂/LOX
- 18 to 100 % for the solid rocket motors

The lower bound for these yields is zero, since the propellants may react or burn without producing mechanical damage.

Although the STS is not being considered for commercial space transportation, Table 5-1 is very useful to illustrate that the yield of a propellant system can vary depending on the failure mode.

Recommended values for TNT equivalency of liquid propellants under selected worst case accident conditions are given in AFR 127-100.⁽⁴⁾ Since AFR 127- 100 addresses the circumstances in handling and storing propellants, it may not apply to launch operations.

TABLE 5-1 ESTIMATED SHUTTLE MAXIMUM CREDIBLE EXPLOSIVES EQUIVALENCIES

<u>Failure Mode</u>	<u>External Tank</u>	<u>% TNT Yield (by weight)</u>
Destruct (Range Safety System)		
Current Design	- Without Orbiter	0.5
	- With Orbiter	1.0
Redesign (Galileo Mission)		0.25
Direct Fall Back on Pad		Not Credible
High Velocity Ground Impact (Intact) (W/O Destruct)		50*
Over Pressurization	- LH ₂ Tank	0.5
	- LOX Tank - Flight	Not Credible
	- Ground	10
SSME (Boattail) Explosion		0.5
Fallover	- Both SRB's Fail to Ignite	38
Tipover	- One SRB Fails to Ignite	38
TPS Failure	- ET - LH ₂ Tank - Barrel	1
	- Aft Dome	0.5
	- LOX Tank	0.5
	- Intertank	10
	SRB - Nose Cone/ Aft Skirt	0
	- Cable Tray (Destruct)	5-1
	- Sep'n Motors, Thermal Curtain, Attach Ring	0.5
SRB - TVC Hardover (Corkscrew - Destruct)		5-1
SRB - Case Rupture	- Adjacent to ET	0.5
	- Elsewhere - Cartwheel	5
	- Separation	0.5
Recontact on Separation - SRB/ET	- Aft	0.5
	- Forward (I/T)	10
	- Orbiter/ET	0.5
<u>Failure Mode</u>	<u>Solid Rocket Motors</u>	<u>% TNT Yield (by weight)</u>
Aft Segment at Impact		18
High Velocity Ground Impact (W/O RSS)		20
Fallover - (Both SRB's Fail to Ignite)		20-50
Tipover - (One SRB Fails to Ignite)		20-100

Source: Briefing, Riehl, 1979 [Ref. 10]

*The yield is a function of impact velocity and can reach 150% for velocities in excess of about 500 feet per second.

The values are presented in Table 5-2, where it should be noted that:

- TNT yields for the same propellant vary depending on the accident conditions. While this variation is consistent with the concept of TNT yield (as discussed above), it is important to select the appropriate value for each set of accident conditions since the yield varies by up to a factor of seven.
- Significant equivalent TNT yields are estimated under the most severe scenarios. These worst case scenarios are very unlikely, however.

For illustration, the recommended TNT yield values are applied to three classes of ELV vehicles of interest: Atlas/Centaur, Delta and Titan. This is presented in Table 5-3, which shows the propellant composition, weight, TNT yield estimate and TNT equivalent weight for each vehicle. Note that :

- for liquid propellants, the yield estimates are based on the recommended guidelines in AFR 127-100 which represent worst cases. Thus, they are inherently conservative.
- For solid propellants, the yield estimates are taken from a compilation of SRM impact detonation history.⁽¹⁾ A range of values (varying over a factor of five) is given to cover a number of accident scenarios.

TNT equivalent weights are obtained by multiplying each propellant weight by its yield. A range of TNT weights is obtained because of the uncertainties in the yields. Such uncertainties are expected in view of the previous discussion of the various factors that affect TNT yield. In reality, the ranges vary from a lower bound of 0 (i.e., no blast) to the upper values (i.e., worst cases) in Table 5-3. To estimate a reasonable value within this range requires an accident-specific analysis, which is not attempted in this generic report.

Finally, note that a hybrid propellant mix technology (liquid oxygen/solid polybutadiene fuel) proposed by AMROC, has been assigned a TNT equivalence of zero by the DOD Explosives Safety Board.

TABLE 5-2. LIQUID PROPELLANT HIGH EXPLOSIVE (TNT) EQUIVALENT YIELDS
(Source Ref. 4, AFR 127-100, Table 5-14)

<u>Propellant Combination</u>	<u>Static Test Stands³</u>	<u>Range Launch Pads³</u>
LO ₂ - LH ₂	60%	60%
LO ₂ - LHx RP-1	Sum of 60% for LO ₂ - LH ₂ plus 10% for LO ₂ - RP-1	Sum of 60% for LO ₂ - LH ₂ plus 20% for LO ₂ - RP-1
LO ₂ - RP-1 or LO ₂ - NH ₃	10%	20% up to 500,000 lbs plus 10% over 500,000 lbs
Inhibited Red Fuming Nitric Acid (IRFNA) - Aniline ²	10%	10%
IRFNA-UDMH ²	10%	10%
IRFNA-UDMH + JP-4 ²	10%	10%
N ₂ O ₄ -UDMH + N ₂ H ₄ ²	5%	10%
N ₂ O ₄ -UDMH + N ₂ H ₄ -Solid ²	5% plus the high explosives equivalent of the solid propellant	10% plus the high explosive equivalent of the solid propellant
Pentaborane + a fuel	10%	20% up to 500,000 lbs plus 10% over 500,000 lbs
Pentaborane + an oxidizer	60%	60%
Tetranitromethane (alone or in combination)	100%	100%
Nitromethane (alone or in combination)	100%	100%
Substitutions	Percentages given above continue to apply where any of the substitutions shown below are made in the basic combination. ⁴	

NOTES:

1. Basis of the table: Developed by the Department of Defense Explosives Safety Board Work Group on Explosive Equivalents for Liquid Propellants. Tetranitromethane and nitromethane are known to be detonable. The net weight of all nonnuclear mass-detonating explosives involved in any configuration, including component of nuclear items, will be added to the above equivalencies, where applicable, in determining required separations. See paragraph 5-26a(5) in Ref. 4 concerning equivalents for hypergolic combinations.
2. These are hypergolic combinations. (Fuel and oxidizers that will ignite with each other.)
3. The percentage factors used for the explosive equivalencies of propellant mixtures at launch pads and static test stands were based on such propellants located above ground and unconfined except for their tankage. Other configurations will be considered on an individual basis to determine applicable equivalencies.
4. Substitutions, alcohols or other hydrocarbons substitute for RP-1; H₂O₂, F, BrF₅, ClF₃, OF₂, or O₃F₃ substituted for LO₂, Monomethylhydrazine substituted for hydrazine or UDMH, or ammonia substituted for any fuel where hypergolic combination results.

TABLE 5-3. ESTIMATED UPPER BOUNDS ON TNT-EQUIVALENT WEIGHTS OF ELV PROPELLANTS

<u>System</u>	<u>Propellants</u>		<u>TNT Yield</u> <u>%</u>	<u>Basis</u> <u>for</u> <u>TNT Yields</u>	<u>TNT Equivalent</u> <u>Weight, klb</u>
	<u>Composition</u>	<u>Weight, klb</u>			
Atlas	RP-1/LO _x	303	10 - 20	a	30 - 60
Centaur	LH ₂ /LO _x	30.7	60	a	18
					48 - 78
<u>Delta</u>					
Booster	Solid (Castor IV)	186	14 - 100 +	b	26 - 186 +
Stage 1	RP-1/LO _x	179	10 - 20	a	18 - 36
Stage 2	Aerozine 50/N ₂ O ₄	13	5 - 10	a	0.7 - 1.3
Stage 3	Solid	2.3	14 - 100 +	b	0.3 - 2.3 +
					45 - 226 +
<u>Titan III</u>					
Stage 0	Solid (UTP-3001 B)	464	14 - 100 +	b	65 - 464 +
Stage 1	Aerozine 50/N ₂ O ₄	294	5 - 10	a	15 - 29
Stage 2	Aerozine 50/N ₂ O ₄	69	5 - 10	a	3.5 - 7
Transtage	Aerozine 50/N ₂ O ₄	9	5 - 10	a	0.5 - 1
					84 - 501 +

Notes on Basis for TNT yield:

(a) Recommended values for liquid propellants in AFR 127-100 (Table 5-14 on pg. 72). It is recognized that these recommended values are based on worst case scenarios and are thus conservative.

(b) Based on data in CIPA Handbook (Ref. 1) for SRM Impact Detonation History (Table 2-1 on pg. 2-6).

Note that the range of TNT yields vary from a lower bound of zero (i.e., no blast) to the upper values given above.

5.2.3 Damage Criteria

Blast waves from accidental explosions can cause damage to people and property (structures) by subjecting them to transient crushing pressures and winds (which cause drag pressures due to the sheer force of the wind). Even though the interactions of the waves with the objects involve very complex phenomena, relatively simple concepts have been used quite effectively to correlate blast wave properties with damage to a variety of targets. The concept states that damage is primarily a function of either the peak overpressure, the impulse or some combination of these two factors.

Guidelines for peak overpressures required to produce failures to structures such as shattering of glass windows and collapse of concrete walls are presented in Table 5-4.⁽¹⁾ Note that a very low pressure (force per unit area) is sufficient to cause damage, mainly due to the large area of such surfaces. Similar criteria are used in the hazard assessment model used in Vol. 3, Ch. 10 of this report.

Criteria for injury of personnel standing in the open are given in Table 5-5.⁽¹⁾ They cover ear drum rupture and lung hemorrhage caused by overpressure and personnel blowdown caused by the impulse imparted by the blast wave, with the concomitant potential of injury due to bruises, lacerations and bone fractures. These data are presented in graphic form in Figure 5-2 and Figure 5-3.⁽¹²⁾ Note that:

- The overpressure required to cause damage decreases (as expected) with the increase in the duration of the positive phase of the blast wave.
- There is a significant variability in the susceptibility of people to such overpressure. Such variability can be accounted for statistically by raising overpressure thresholds to ensure higher levels of lethality. This should be done carefully to maintain a realistic approach to analysis.

Finally, blast wave characteristics (Section 5.2.1) can be combined with the present damage criteria in order to estimate the extent of the damage (in feet) as a function of various equivalent weights of TNT. Typical results are shown in Figure 5-4 for eardrum rupture, lung damage, etc. Similar data are used in the next section and in Ch. 10, Vol.3 to illustrate the assessment of both property damage and personnel injury over a range of accident conditions.

TABLE 5-4. CONDITIONS OF FAILURE OF PEAK OVERPRESSURE-SENSITIVE ELEMENTS (Ref. 1)

<u>Structural Element</u>	<u>Failure</u>	Approximate Incident Blast Overpressure kPA (psi)
Glass windows, large and small	Shattering usually, occasional frame failure	3.4-5.9 (0.5 - 1)
Corrugated asbestos siding	Shattering	5.9-13.8 (1 - 2)
Corrugated steel or aluminum paneling	Connection failure followed by buckling	6.9-13.8 (1 - 2)
Wood siding panels, standard house construction	Usually failure occurs at main connections allowing a whole panel to be blown in	6.9-13.8 (1 - 2)
Concrete or cinder-block wall 20.3 or 30.5 cm (8 or 12 in) thick (not reinforced)	Shattering of the wall	13.8-20.7 (2 - 3)
Self-framing steel panel building	Collapse	20.7-27.6 (3 - 4)
Oil storage tanks	Rupture	20.7-27.6 (3 - 4)
Wooden utility tanks	Snapping failure	34.5 (3 - 4)
Loaded rail cars	Overturning	48.3 (7)
Brick wall panel, 20.3 or 30.5 cm (8 or 12 in) thick (not reinforced)	Shearing and flexure failures	48.3-55.2 (7 - 8)

TABLE 5-5. AIR-BLAST CRITERIA FOR PERSONNEL STANDING IN THE OPEN (Ref. 1)

<u>Criteria</u>	<u>Physical Parameters Dose</u>	<u>Remarks</u>
<u>Direct Overpressure Effects:</u>		
1% Eardrum Rupture	23 kPa (3.4 psi)	Not duration sensitive except possibly for durations of less than 1 msec. Not a serious lesion.
50% Eardrum Rupture	110 kPa (16.0 psi)	Some of the ear injuries would be of a severe form.
Threshold of Lung Hemorrhage	69 kPa (10.0 psi)	69 kPa (10 psi) applies to blasts of long duration, over 50 msec; 138-207 kPa (20-30 psi) required for 3-msec duration waves; not a serious lesion.
1% Mortality	186 kPa (27 psi)	186 kPa (27 psi) applies to blasts of long duration, over 50 msec; 414-483 kPa (60-70 psi) required for 3-msec duration waves. A high incidence of severe lung injuries.
<u>Displacement Effects:</u>		
No Personnel Blowdown	8.62 kPa-msec (1.25 psi-msec)	At this dynamic-pressure impulse, man would attain a peak horizontal velocity of 0.09 m/s (0.3 fps)
50% Probability of Personnel Blowdown	57.2 kPa-msec (8.30 psi-msec)	At this dynamic-pressure impulse, man would attain a peak horizontal velocity of 0.61 m/s (2.0 fps).
1% Probability of Serious Injury from being Blown down	372 kPa-msec (54 psi-msec)	At this dynamic-pressure impulse, victim would attain a peak horizontal velocity of 4 m/s (13 fps); serious injury (bone fracture or rupture of internal organs) could occur from impact with the ground; high probability of minor injuries such as bruises and lacerations.

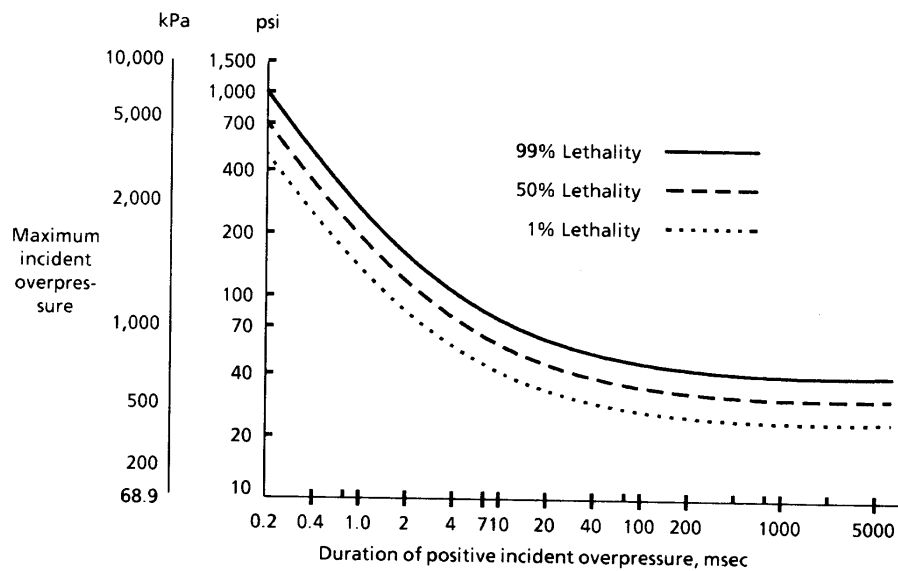


FIGURE 5-2. LETHALITY CURVES PREDICTED FOR 154 LB. PERSON IN FREE-STREAM SITUATIONS (Ref. 12)

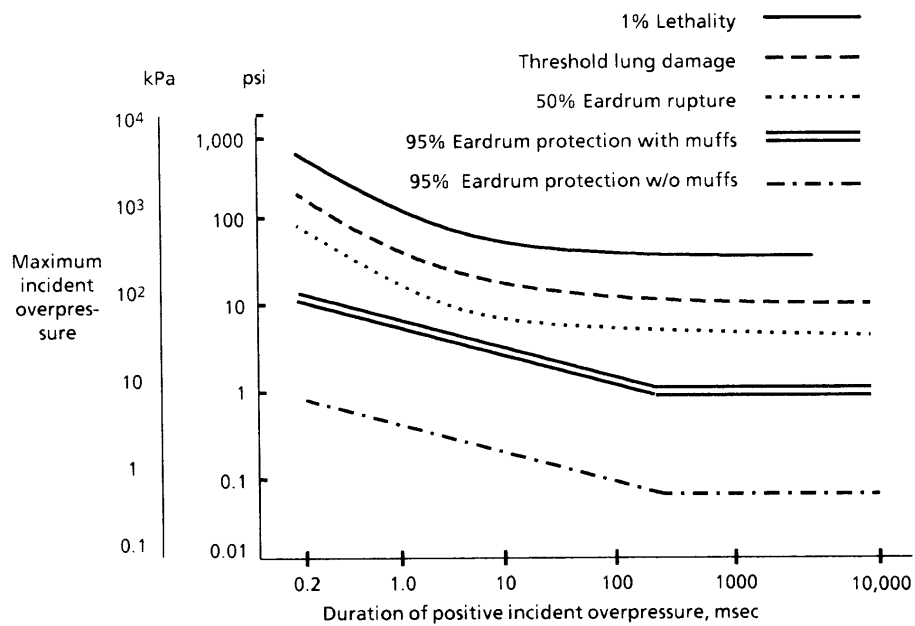


FIGURE 5-3. LETHALITY AND DAMAGE/INJURY CURVES PREDICTED FOR 154 LB. PERSON IN FREE-STREAM SITUATION (Ref. 12)

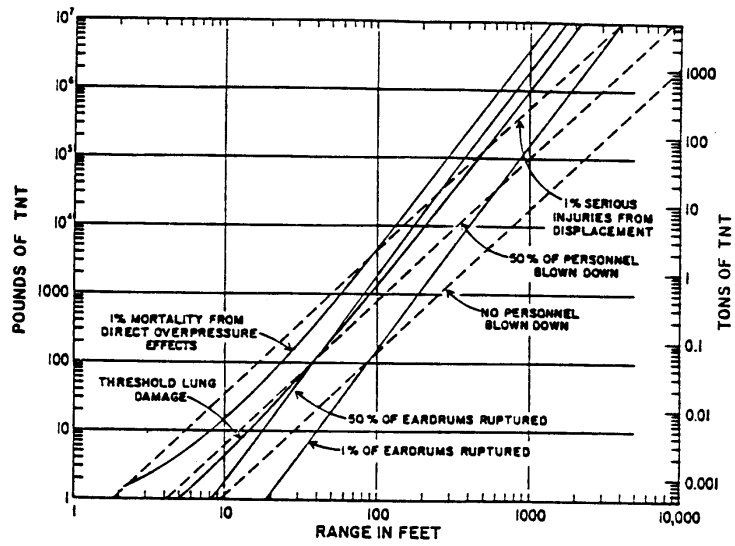


FIGURE 5-4. AIR-BLAST CRITERIA FOR PERSONNEL STANDING IN THE OPEN (Ref. 12)

5.2.4 Variation of Explosion Hazards with Time from Liftoff

As noted, launch hazards decrease with time into the flight. This point is illustrated in this section for potential third party damage due to an accidental explosion of an ELV. The variations of other hazards with time are not discussed.

Data are used for a typical Delta ELV system flight profile and propellant consumption rate as a function of time elapsed after liftoff.⁽¹³⁾ However, qualitatively, the discussion applies equally well to other ELV systems.

The outcome of an accident is usually determined by the specific circumstances present at the time and location of the accident. Usually, there are a number of variations for these circumstances which can lead to a number of outcomes. In this illustration, the analysis is simplified to focus on the effects of "time into flight."

The calculations presented below are also based on a number of assumptions selected to make the analysis workable. For example, for the sake of simplicity, it is assumed that all of the propellants remaining on board will explode instantly (this corresponds to a worst case calculable explosion scenario). In reality, the situation is more complicated:

- some of the propellant may explode initially, producing fragments that may explode later upon impact with the ground (secondary explosions);
- some of the propellant may burn in a fireball; and
- some of the hypergolic propellant may disperse in the environment without reacting, posing toxic risks or dispersing harmlessly.

Another example of a simplifying assumption is to represent different circumstances occurring at various times into flight by simply changing the TNT yield. The yield is increased when the circumstances (such as failure mode, mixing rate or impact speed) favor a stronger explosion (as described in more detail below).

Note that each scenario can be associated with a vehicle failure mode and is likely to occur with a particular probability value (Section 5.6). Thus, although the discussion below makes no explicit mention of probabilities, the predicted results are tied to a particular probability value.

Therefore, three key changes can be identified as time elapses from liftoff: the vehicle altitude (and down-range distance), the quantities of propellants remaining on board and the explosive potential of these propellants. These changes are illustrated in Figure 5-5 and are discussed below.

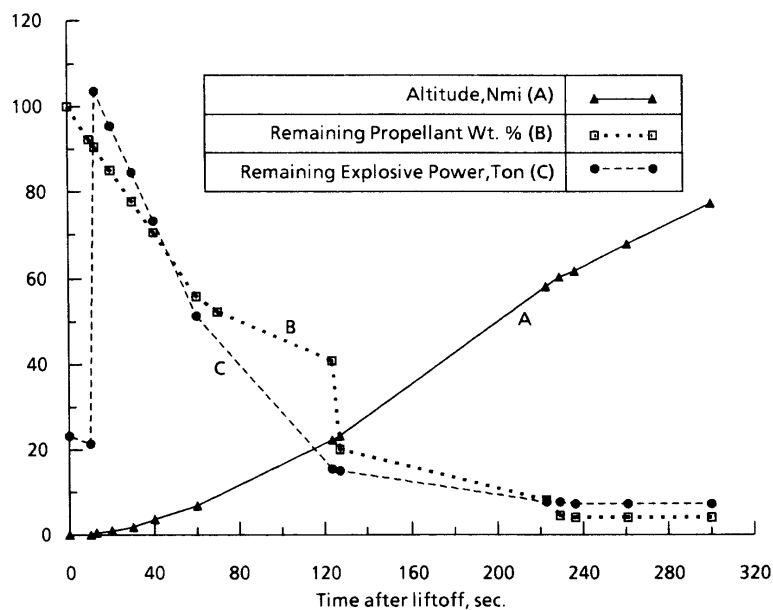


FIGURE 5-5 POTENTIAL EXPLOSION HAZARD AS A FUNCTION OF TIME (DELTA ELV)

First, the vehicle altitude increases very rapidly with time into flight -- reaching roughly 20 nm. in the first 2 minutes, as illustrated by curve A in Figure 5-5, which shows a typical flight profile for a Delta mission.⁽¹³⁾ Furthermore, the location of launch sites and the direction of launch are usually selected so the vehicle moves away from population centers. Thus, the "separation" distance between the vehicle and the communities potentially vulnerable, in case of a vehicle accident, increases with time.

Second, as time elapses from liftoff, the quantity of propellants remaining on board decreases very rapidly due to their rapid consumption by the rocket booster and other engines. The total weight of all propellants remaining on board is illustrated by Curve B in Figure 5-5. Note that the total remaining propellant weight decreases by about 50% within 2 minutes from liftoff.

Third, the explosive potential (or TNT yield) of a given quantity of propellant may change as time elapses from liftoff. As discussed earlier (Sec. 5.2.2), the TNT yield of a propellant in an accidental explosion depends on its properties, as well as on a variety of other factors, determined by the details of the accident scenario. Example of such factors include: the sizes of solid propellant fragments their impact speed, the rate and extent of mixing of liquid propellants, the degree of confinement, etc. In fact, the significance of TNT yields, how they are estimated and the pertinent ranges of values given in the published literature were discussed in Section 5.2.2.

Determination of TNT yield at various times after liftoff requires an extensive analysis. First, identify the type of failures and accident scenarios that are likely to occur and second, estimate the yield for each scenario and each propellant system based on historical accident data, test data, experience and engineering judgment. Such an analysis was done for the Space Shuttle system by the Explosive Equivalency Working Group established by NASA in 1978, as discussed in Section 5.2.2. Ideally, the same type of analysis for each ELV type is needed to establish pertinent explosive yields were the accident to occur at various times from liftoff. However, for simplicity, another approach which is not as rigorous, but may suffice, is used to illustrate the explosive yield dependence on time from liftoff.

Table 5-2 in Section 5.2.2 lists upper limits for TNT yields for ELV propellants reported in the literature. The lower bound for these yields is zero (%), since the propellants may react or burn without producing mechanical damage. The range of upper values for the Delta vehicle propellants are:

- 10 to 20% for RP-1/LOX (Stage I)
- 5 to 10% for Aerozine-50/N₂O₄ (Stage II)
- 14 to 100% for the solid rocket motors (Booster and Stage III)

Note that each point within these ranges can be associated with a particular accident scenario which, in turn, may be associated with a specific time from liftoff. For example, when a vehicle (or its fragments) falls back on the pad soon after liftoff, the speed at ground impact is a key factor in determining the likelihood of detonating the solid propellants. It is known that an impact speed of 300 ft/sec is required to detonate solid propellants and produce significant yields. In order to reach such terminal speeds in free-fall, a vehicle would have to start at an altitude of approximately 1400 ft (assuming no drag). This altitude would be reached in about 12 seconds after liftoff. Thus, if the vehicle falls back onto the pad in the first 12 seconds (or so), a low yield is anticipated, while if it falls back at a later time, a higher yield is anticipated. Following this reasoning, the yields corresponding to these two situations are assumed (for simplicity) to be the upper and lower values of the ranges listed above for the three propellant types in the Delta vehicle. Thus, the yields would be:

- 10, 5 and 14% (respectively for the 3 types of propellants) in the first 0 to 12 sec after launch;
- 20, 10 and 100%, respectively, at later times into flight.

By multiplying these yields with the amount of propellants remaining on board, the potential explosive energy (in terms of equivalent pounds of TNT) is estimated as a function of time from liftoff as illustrated by Curve C in Figure 5-5. Note that the explosive potential starts at a low value (because of the low yield); then increases because of the increase in yield corresponding to higher impact speed; finally it decreases because of the decrease in the quantity of propellant remaining on board.

Using the potential explosive energy determined above, the overpressure field around the explosion point was estimated following the analysis outlined in Section 5.2.1. It was assumed that the entire vehicle will explode at altitude and as one mass (a more realistic assumption is a smaller explosion in flight, breaking up the vehicle in fragments that will explode upon ground impact). It was also assumed that any reflection or focusing of the shock wave would have a negligible effect on the overpressure field.

For these assumed explosion conditions, the "hazard" distances at which critical overpressures are reached are shown as a function of time in Figure 5-6. Three overpressure levels are used:

- 1.5 psi, for collapse of light weight structures (Curve B)
- 0.35 psi, for window breakage with a probability of 50% (Curve C)
- 0.20 psi, for window breakage with a probability of 10% (Curve D)

The vehicle altitude from Figure 5-5 is also shown as Curve A in Figure 5-6 for reference.

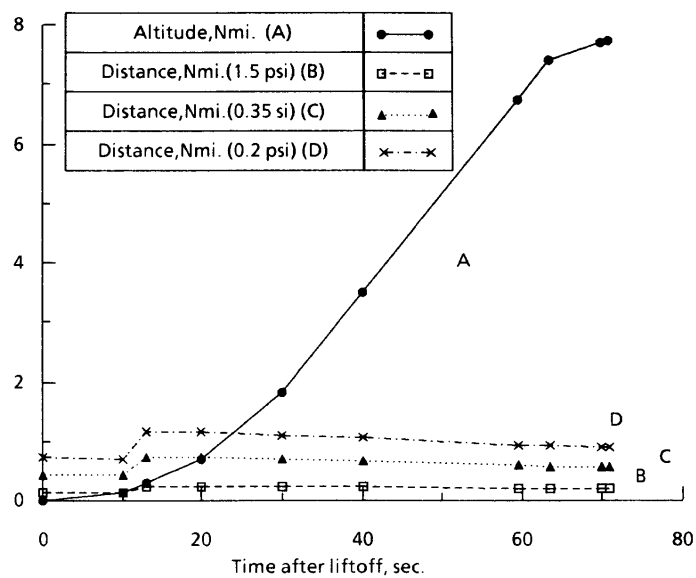


FIGURE 5-6 OVERPRESSURE AS A FUNCTION OF TIME (DELTA ELV)

In Fig. 5-6, the hazard distances first increase with time, and then decrease -- following the behavior of the potential explosive energy profile which is shown in Fig. 5-5. Furthermore, Fig. 5-6 can be interpreted as follows:

- in approximately the first 25 seconds, damage such as window breakage is possible in a distance of approximately 1 nm. from the launch pad (or the location of vehicle impact with ground).
- at later times, key scenarios are:
 - a- all the propellant explodes at the vehicle altitude. The potential mechanical damage at ground level is negligible (even if maximum yield is assumed) because of the high altitude of the vehicle and its the large separation from ground.
 - b- the vehicle falls back to Earth as one piece and explodes. This is a very unlikely scenario since the vehicle will breakup under the aerodynamic forces produced by the fall. Even in such a worst case scenario, Figure 5-6 suggests that the maximum overpressure distance will be less than 1 nm. in the first 25 to 60 sec time frame; much smaller yet at later times because of the rapid consumption of propellants with time of flight. The location of the impact point will be governed by vehicle trajectory during the fall, which in turn depends on a number of factors as discussed in Section 5.3.
 - c- the vehicle breaks up at altitude, producing fragments, some of which may detonate as they impact ground. The hazard of item b above is now distributed over a broader region determined by the impact points of the fragments. The overpressure hazard distances around each impact point will be smaller than in b above. They will depend on additional factor such as number and size of fragments and their rates of consumption during their fall. This is further discussed in Section 5.3.

Off-range damage in any of the above cases will depend on the presence of population centers within a radius (of the explosion center) equal to the above distances (see Sec. 5.6).

Generally, the hazard from propellant explosion decreases rapidly with time into flight, except for the first 10 to 25 seconds. Activation of the Flight Termination System is likely to further reduce such explosion hazards by dispersing the

propellant. Typically, the FTS is not activated during the first 8-12 seconds (depending on ELV, mission and site) in order to avoid damage to the pad facilities. This subject is discussed in more detail in Ch. 3, Vol. 1 and Ch. 10, Vol. 3.).

5.3 DEBRIS HAZARDS

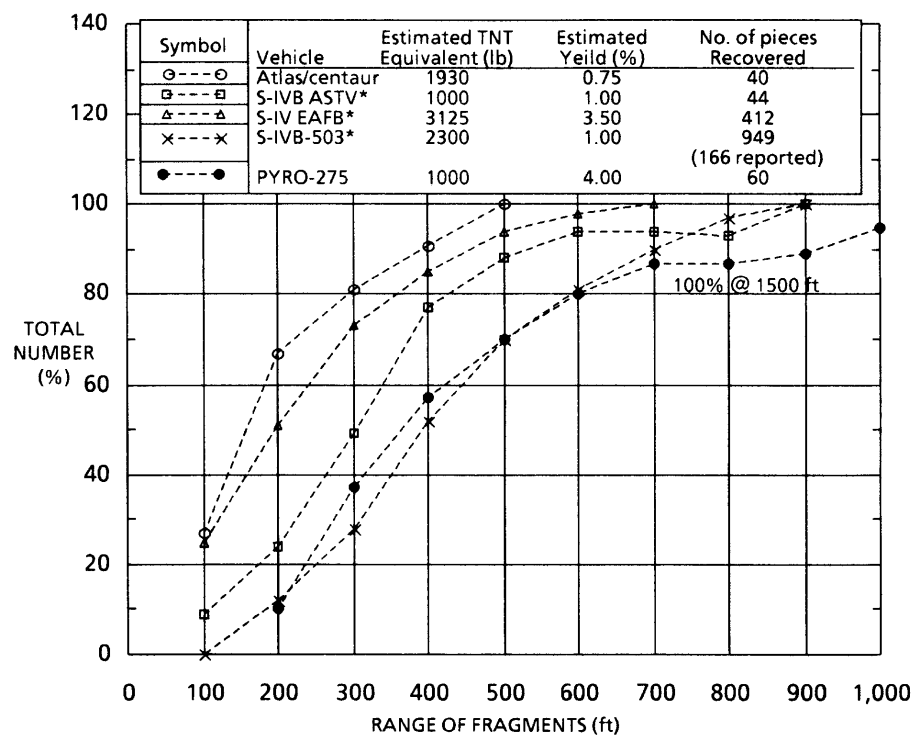
A debris hazard exists even for a normal successful launch, primarily from jettisoned stages, shrouds and other components. These can be expected to impact within the impact limit boundaries of the flight corridor. The flight corridor is specified by applying safety considerations to the mission flight requirements, as discussed in Ch. 2, Vol. 1. Thus, hazards which cannot be eliminated are controlled. Since the launch facilities are located so that the vehicles will fly over largely uninhabited areas and oceans, the risks to third parties in normal operational situations are very low .

A debris hazard also exists due to failure modes such as malfunction turns (from gradual to tumbling turns) and premature thrust termination (from an accidental subsystem failure, commanded thrust termination or commanded vehicle destruction). Debris may be created either from breakup of the vehicle due to excessive aerodynamic pressure or explosion (accidental or commanded destruct). Major issues in assessing debris hazards include: what is the number, weight and shape of fragments? Where will they land? What is their impact force upon landing? What is their impact in terms of structure penetration and lethality?

Illustrative examples of debris data from selected space vehicle explosions and test data (occurring at or near ground level) are shown in Figure 5-7 and Figure 5-8. These figures show the total number and weight distributions of fragments (respectively) as a function of range (i.e., distance). These distances were determined by the forces of the explosions.

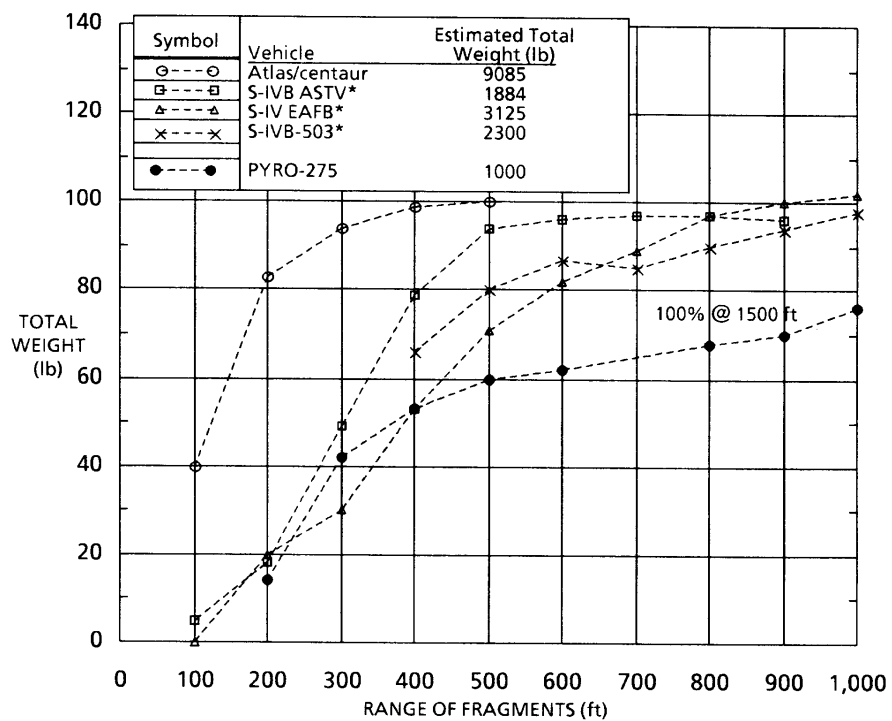
Clearly, when a vehicle is in flight at significant altitude, the debris will land over a much larger area than in Figures 5-7 and 5-8. The distribution of debris impacts is dependent upon the forces acting on the fragments. Initially, the velocity vector of the vehicle is of primary importance and this contribution is affected by the velocity vectors resulting from the turns, tumbling and/or explosions. Thereafter, the effects of the atmosphere on the fragments during free fall (which depend on wind and the fragment size, shape and mass) become important. These issues lead to uncertainties in the fragment impact distribution which can be attributed to four basic sources:

- (1) uncertainty in the vehicle state vector at vehicle breakup or destruct;



* Solid propellant used in Project Sophy

FIGURE 5-7. PERCENTAGE OF TOTAL NUMBER OF VEHICLE FRAGMENTS WITHIN RANGE INDICATED (Ref. 1)



* Solid propellant used in Project Sophy

FIGURE 5-8. PERCENTAGE OF TOTAL WEIGHT OF VEHICLE FRAGMENTS WITHIN RANGE INDICATED (Ref. 1)

- (2) uncertainty in any destruct velocity imparted to the fragment by a destruct system (or explosive failure);
- (3) uncertainty in the atmospheric environment during free fall; and
- (4) uncertainty in the fragment size, aerodynamic lift and drag.

Furthermore, impacting launch vehicle fragments can be divided into four categories:

- (1) inert pieces of vehicle structure;
- (2) pieces of solid propellant (some of which may burn up during free fall);
- (3) vehicle structures which contain propellant (solid or liquid) that may continue to burn after landing (but are non-explosive). They pose the risk of starting secondary fires at the impact points; and
- (4) fragments which contain propellant and which can explode upon impact (if their impact velocity is greater than roughly 300 ft/s).

The casualty area of an impacting fragment is the area about the fragment impact point within which a person would become a casualty. Casualties may result from a direct hit, from a bouncing fragment, from a collapsing structure resulting from an impact on a building or other shelter, from the overpressure pulse created by an explosive fragment, from a fire or toxic cloud produced by the fragment or some combination thereof. The hazard area is increased if a fragment has any significant horizontal velocity component at impact which could result in bouncing or other horizontal motion near ground level.

Casualty area is also affected by the sheltering of people by structures. Structures may be divided into classes (for computational purposes) depending on the degree of protection they can afford.

Clearly, estimating a casualty expectation is a complex computational problem. Different Ranges approach the problem in different ways depending on the needs of the Range. Computer models may be used, but the sophistication varies greatly from Range to Range. A computer model called LARA (Ref. 9) treats casualty areas analytically and is presented in other chapters (Vol. 2, Ch. 4, and Vol. 3, Ch. 10).

5.4 FIRE HAZARDS

The fire hazards of accidentally released solid and liquid propellants depend on the details of the accident scenario including: the thermodynamic state of the propellant, the amount

of the release, vehicle location and speed (on launch pad versus in flight), the presence of confining surfaces and ignition sources, etc. The major types of fires that can develop are:

- Fireball: where burning occurs in a ball of fire that expands and rises in the air (due to buoyancy forces) until the propellant is consumed.
- Pool fire: where a film of propellant is formed on the ground and burns with a flame attached to the film.
- Vapor cloud fire: where ignition is delayed and vapors are carried away by prevailing winds, thus forming a flammable cloud that may ignite at a later time.
- Various combinations of the above fires.

These fires are discussed below.

5.4.1 Fireballs

Fireballs are produced when the propellant is quickly vaporized or atomized. These conditions include flash vaporization of pressurized liquids and releases during flight at high speed. The vapors or fine droplets can then rise under the effects of buoyancy as they burn in the fireball.

The main damage mechanism is thermal radiation to people and property. Another damage mechanism is firebrands from burning solid propellants and hot debris which might start secondary fires where they land. A third damage mechanism is impact damage by vessel fragments which have been reported to travel large distances. Overpressure may also develop due to the initial high rate of energy release associated with vessel failure, but it is usually insignificant.

The damage potential depends on key fireball parameters such as diameter, rise rate, duration and temperature or emissive power. These parameters have been quantified in several experimental and analytical studies.⁽¹⁾ In fact, the ball diameter was found to scale roughly with the 1/3 power of the weight of released propellant.

The chemical composition of the products of combustion depend on the chemical composition of the propellants. The combustion products contain mainly water vapors and oxides of carbon and nitrogen. Thermal radiation emitted in the form of water vapor will be (partly) reduced by moisture absorption in the atmosphere. The transmitted radiation can impact people and structures. Table 5-6 shows critical radiation fluxes required to cause burn injury and start secondary fires (such as by igniting fuels placed inside and outside buildings). Note that as the exposure time increases, the required radiant flux decreases, as expected.

**TABLE 5-6. MINIMUM CRITICAL RADIANT EXPOSURES NECESSARY TO IGNITE OR DAMAGE
VARIOUS TARGETS (Source: Ref. 1)**

CRITICAL IRRADIANCE, Btu/ft²sec (cal/cm²sec)

Exposure (seconds)	Int. Building Fuel	Ext. Building Fuel	Open Stacks of propellants	Human Beings	Aircraft
10	5.89 (1.60)	4.64 (1.26)	2.77 (0.75)	8.33 (2.26)	4.79 (1.30)
20	3.91 (1.06)	3.87 (1.05)	1.99 (0.54)	5.77 (1.51)	2.39 (0.65)
30	3.02 (0.82)	3.50 (0.95)	1.62 (0.44)	4.39 (1.19)	1.59 (0.43)
40	2.62 (0.71)	3.28 (0.89)	1.40 (0.38)	3.72 (1.01)	1.40 (0.38)
50	2.32 (0.63)	3.13 (0.85)	1.29 (0.35)	3.32 (0.90)	1.22 (0.33)
60	2.21 (0.60)	3.02 (0.82)	1.18 (0.32)	3.09 (0.84)	1.03 (0.28)
70	2.18 (0.59)	2.88 (0.78)	1.11 (0.30)	2.91 (0.79)	0.94 (0.255)
80	2.14 (0.58)	2.80 (0.76)	1.03 (0.28)	2.80 (0.76)	0.856 (0.235)
90	2.10 (0.57)	2.69 (0.73)	0.92 (0.25)	2.69 (0.73)	0.81 (0.22)
100	2.06 (0.56)	2.65 (0.72)	0.88 (0.24)	2.58 (0.70)	0.77 (0.21)
110	2.03 (0.55)	2.62 (0.71)	0.85 (0.23)	2.47 (0.67)	0.756 (0.205)
120	1.99 (0.54)	2.58 (0.70)	0.81 (0.22)	2.36 (0.64)	0.74 (0.20)
130	1.95 (0.53)	2.54 (0.69)	0.79 (0.215)	2.29 (0.62)	0.726 (0.197)
140	1.92 (0.52)	2.51 (0.68)	0.77 (0.21)	2.21 (0.60)	0.719 (0.195)
150	1.88 (0.51)	2.49 (0.675)	0.756 (0.205)	2.14 (0.58)	0.704 (0.191)
160	1.84 (0.50)	2.47 (0.67)	0.74 (0.20)	2.06 (0.56)	0.697 (0.189)
170	1.84 (0.50)	2.45 (0.665)	0.719 (0.195)	1.99 (0.54)	0.693 (0.188)
180	1.84 (0.50)	2.43 (0.66)	0.712 (0.193)	1.95 (0.53)	0.689 (0.187)
190	1.84 (0.50)	2.41 (0.655)	0.708 (0.192)	1.92 (0.52)	0.686 (0.186)
200	1.84 (0.50)	2.40 (0.65)	0.70 (0.190)	1.92 (0.52)	0.682 (0.185)
300	1.84 (0.50)	2.33 (0.631)	0.659 (0.179)	1.92 (0.52)	0.667 (0.181)
600	1.84 (0.50)	2.29 (0.621)	0.641 (0.174)	1.92 (0.52)	0.645 (0.175)

5.4.2 Pool Fires

Pool fires are produced when liquid propellants are accidentally spilled on the ground such as:

- from a vehicle in pre-launch phase: this scenario is outside the scope of this study since its impact is not likely to extend outside the Range boundaries.
- from ground operations such as propellant transport to the Range and storage, handling and transfer within the Range. In this case, the impact may occur outside the Range boundary.

A spilled liquid will spread on the ground under the effect of gravity, filling small-scale crevices in a ground with surface roughness or large-scale depressions in an undulating terrain. While spreading, cryogenic propellants (such as liquid hydrogen and oxygen) will boil violently due to heat transfer from the relatively warm ground. A propellant at ambient temperature (such as RP-1) will evaporate more slowly. Some flash vaporization of cryogenic liquids will also occur because their vessels are usually maintained at slightly above atmospheric pressure.

Ignition produces a pool fire with a flame base which spreads along with the liquid film and a flame height determined by the rate of evaporation and the rate of mixing of fuel and oxidizer. The overall character of such a pool fire is essentially a turbulent diffusion flame which may continue to expand on flat ground (or remains stationary if the liquid has accumulated in a depression area) until it runs out of fuel.

The danger of pool fires consist of thermal radiation to people and property (as in the case of fireballs) and direct flame impingement on structures near the fire.

5.4.3 Vapor Cloud Fires

In the pool fire scenario described above, if:

- the liquid pool does not ignite immediately after the release, because of lack of an ignition source; and
- the released propellant has a high vapor pressure such as liquid hydrogen, oxygen, nitrogen, air or methane which boil due to heat transfer from the environment and not from a fire;

then, a large amount of vapor will be produced and transported by prevailing winds to form a vapor cloud. In this scenario, the resulting cloud is elongated in shape and is called a "plume". Its leading edge advances with the wind and its trailing edge is formed at the evaporating pool (the source of the vapors). As the leading edge moves further downwind, ambient air is entrained in the cloud, thus increasing its volume and decreasing the vapor concentration. This process is called atmospheric dispersion and is discussed further in the next section.

If a flammable cloud encounters an ignition source, a fire will spread through the cloud, engulfing in flames whatever is contained in the cloud. This is referred to as a vapor cloud fire. Under some conditions (particularly the presence of obstructions or confinement in the cloud) overpressure can be produced, posing the added risk of mechanical damage.

Alternatively, as the cloud disperses, the vapor concentration may drop below the flammable limit prior to encountering an ignition source. Thus, the hazard is dissipated without any adverse impact.

5.5 TOXIC VAPOR CLOUDS

The evaluation of the toxicity of any material is a very complex subject. Toxicity data are very sparse and questionable except for the common toxins. When available, they are usually for continuous exposures as one would find in a factory environment and not for the short exposures characteristic of launch operations.

Still, the issue is of great interest because toxic materials may be released during ELV launches as combustion products, or in the event of an accident, as uncombusted propellants. The most notorious ones are hypergolic liquid propellants such as monomethyl hydrazine, Aerozine-50 and nitrogen tetroxide.

Their chemical properties and toxic Threshold Limit Values (TLV) are listed in Appendix B along with other characteristics of interest. If such materials are released in the environment, they may be carried by the wind and travel windward as they disperse. This atmospheric dispersion is described below.

5.5.1 Atmospheric Dispersion

Over the years, the subject of atmospheric dispersion has been studied extensively in connection with air pollution studies from power plants and automotive vehicles. These studies addressed the case of continuous releases from normal operations where pollutant concentrations were monitored over long periods of time.

In this study, the interest is mainly in larger uncontrolled "instantaneous" releases (as would occur in an accident). Then, a large amount of potentially noxious vapor may be produced and transported by prevailing winds to form a vapor cloud. There are two main types of vapor clouds:

- a "plume": an elongated cloud whose the leading edge travels with the wind, while the trailing edge remains stationary at the source of the vapors. Conditions which produce a plume are described in the preceding section;
- a "puff": a more or less spherical cloud where both leading and trailing edges move together downwind.

In reality, a combination of these two cloud geometries may occur, depending on accident conditions.

As the cloud travels downwind, ambient air is entrained in the cloud; this increases its volume and decreases the vapor concentration. The process can be further complicated by chemical interactions among hypergolic vapors and between vapors and entrained air.

Such cases of large "instantaneous" releases have also been studied experimentally. Large scale tests involving the spillage of large quantities of chemicals were carried out and concentrations were measured downwind. The most notable tests, carried out as part of national and international programs include:⁽²¹⁾

- (1) the liquefied natural gas (LNG) dispersion tests at the Naval Weapons Center, China Lake, California, for the US Department of Energy;
- (2) the ammonia spill tests at the above location for the Fertilizer Institute and the US Coast Guard;
- (3) the Porton Down tests in England involving the instantaneous release of Freon;
- (4) the heavy gas dispersion trials on behalf of the Health and Safety Executive of the British Government and other participants; and
- (5) the LNG spill tests conducted by Shell UK Ltd. at Maplin Sands, England.

Based on such tests, it is recognized that cloud dispersion depends mainly on:

- ambient conditions such as wind, atmospheric stability and local terrain.
- the buoyancy of the vapor cloud. It is important to determine whether the cloud is lighter or heavier than air because the former will disperse much faster than the latter. The presence of aerosols (fine droplets sprayed from the spilled liquid) increases the effective density of the cloud and modifies its dispersion characteristics. Also, cloud density may vary in space and time so that some portions may be lighter than air and others heavier.
- the size and location of the release, i.e., whether it is on ground level (from an accident on the launch pad) or from an elevated altitude (from an accident in flight).

There are several models in the literature describing the dispersion behavior of heavier-than-air gases under a wide range of conditions.^(14 a, b, c) Models which discuss the dispersion of vapors released passively (as from a boiling pool of liquid) include Van Ulden,⁽¹⁵⁾ Britter,⁽¹⁶⁾ and Colenbrander.⁽¹⁷⁾ There are also models in the air pollution literature dealing with release of neutral and positively buoyant vapors from stacks.

In general, the dispersion of vapors in the far-field (after sufficient dilution) can be predicted with reasonable accuracy by the standard Gaussian models of Pasquill⁽¹⁸⁾ and Gifford.⁽¹⁹⁾ However, in the near-field, these models have to be modified to take into account the effects of initial gravitational spreading, jet mixing or the effects of aerosol evaporation.⁽²⁰⁾

5.5.2 Rocket Exhaust Products

Most of the combustion products from rocket engines are harmless or unlikely to exist in concentrations which would affect the health and safety of third parties. These combustion products may include:

- water and water vapors
- nitrogen
- hydrogen
- carbon monoxide and dioxide
- hydrogen chloride
- aluminum oxide

Of these combustion products, carbon monoxide and hydrogen chloride may be considered hazardous. Aluminum oxide is not toxic, but may contribute to certain lung diseases if exposure persists over time. The remaining combustion products are not

dangerous unless present in sufficient concentration to cause asphyxiation, which is not the case. Threshold Limit Values (TLV) for major combustion products are given in Table 5-7 for various exposure durations for both controlled (Range personnel) and uncontrolled (third party) populations.

For illustration, Figure 5-9 shows results from a model using the NASA/MSFC (buoyant-rise, multilayer dispersion model of exhaust products) to compute peak instantaneous concentrations of hydrogen chloride as a function of downwind distances from the launch pad for sea breeze meteorological conditions and certain vehicle configurations. Also, Figure 5-9 shows the exposure criteria limit (as given in Table 5-7) for 10 minute-exposure of uncontrolled populations (third parties). Note that this limit is not exceeded at downwind distances of interest. In 1985, the Committee on Toxicology, Board on Toxicology and Environmental Health Hazards, Commission on Life Sciences, National Research Council published a document entitled "Emergency and Continuous Exposure Levels for Selected Airborne Contaminants," Volume V.^(20a) This document updates recommendations for public exposure to the hydrazines and creates a new category, Short-term Public Emergency Guidance Levels (SPEGL's) for up to 24 hours for hydrazine propellants. The data in this document affects values for the uncontrolled population exposure to hydrazine shown in Table 5-7.

5.5.3 Releases During Accident Conditions

In the case of a near-pad explosion, all of the propellant is unlikely to be combusted. Thus, a vapor cloud containing vapors and aerosols of hydrazine, nitrogen tetroxide and hydrocarbon fuels might result. Other chemicals such as fuel additives and contaminants may also be present. These materials are toxic (see TLV values listed in Appendix B) and in high concentrations may cause adverse health effects, particularly if meteorological conditions at the time of the accident do not favor rapid dispersion to below toxic levels.

The Titan 34 D explosion at WSMC of April 18, 1986, produced a vapor cloud containing toxic Aerozine-50 (Unsymmetric dimethylhydrazine and hydrazine blend) and nitrogen dioxide. There was no verified exposure of third parties to toxic concentrations exceeding established limits. However, reports indicate that doctors examined 74 people for possible exposure to the clouds and two were kept in the hospital for observation (see also Ch. 10).

TABLE 5-7. EXPOSURE CRITERIA FOR SOME COMBUSTION PRODUCTS AND PROPELLANTS

Substance	Controlled Populations (a)		Uncontrolled Populations (b)				
	TLV, (c) ppm	Short-Term	Exposure From		Emergency		
		Emergency limits, ppm 10 min. 30 min. 60 min.	Ordinary operations, ppm 10 min. 30 min. 60 min.	Exposure, ppm 10 min. 30 min. 60 min.	Exposure, ppm 10 min. 30 min. 60 min.		
HCl	3	30 20 10	4 (d)	2 (d)	2 (d)	3 (d)	3 (d)
CO	50	200			30 (e)		125 (g)
mg/m ³	10	50 (g) 25 (g)		--		--	
NO ₂ (N ₂ O ₄)	3	30 20 10	1 (f)	1 (f)	1 (f)	5 (f)	2 (f)
Hydrazine	0.1	100 20 10	1 (g)				
UDMH	0.5	100 50 30	0.5 (g)			--	--
AlCl ₃ (mg/m ³)	10 (h)	--		--		--	--

(a) Controlled populations consist of persons with known medical histories, subject to periodic health checks, and generally under the control of the responsible agency. Such persons are normally employees with jobs that will potentially result in exposure to known contaminants.

- (b) Uncontrolled populations consist of persons with unknown medical histories, not subject to periodic health checks, and not generally controlled by the responsible agency. The general public is included in this classification.
- (c) No short duration exposure criteria for controlled populations.

(d) While there are no criteria for short-term exposures, TLV's are thought to be conservative for short duration exposures of controlled populations for relatively infrequent normal operations. TLV's are also considered ceiling values not to be exceeded. TLV's are time-weighted concentrations for 7 or 8 hour work days and a 40-hour work week, except that the values for HCl and NO₂ are also considered ceiling values not to be exceeded. Threshold Limit Values (TLV) are time-weighted concentrations for controlled populations appear applicable for ordinary launch operations. No short duration exposure criteria for controlled populations appear applicable for this classification.

(d) While there are no criteria for short-term exposure of uncontrolled populations to HCl which have official standing, the values quoted here have been proposed by a responsible organization after careful study of the problem. Based on 1.5% Carboxyhaemoglobin in 1 hour exposure.

e) Based on 1.5% Carboxyhemoglobin in 1 hour exposure.

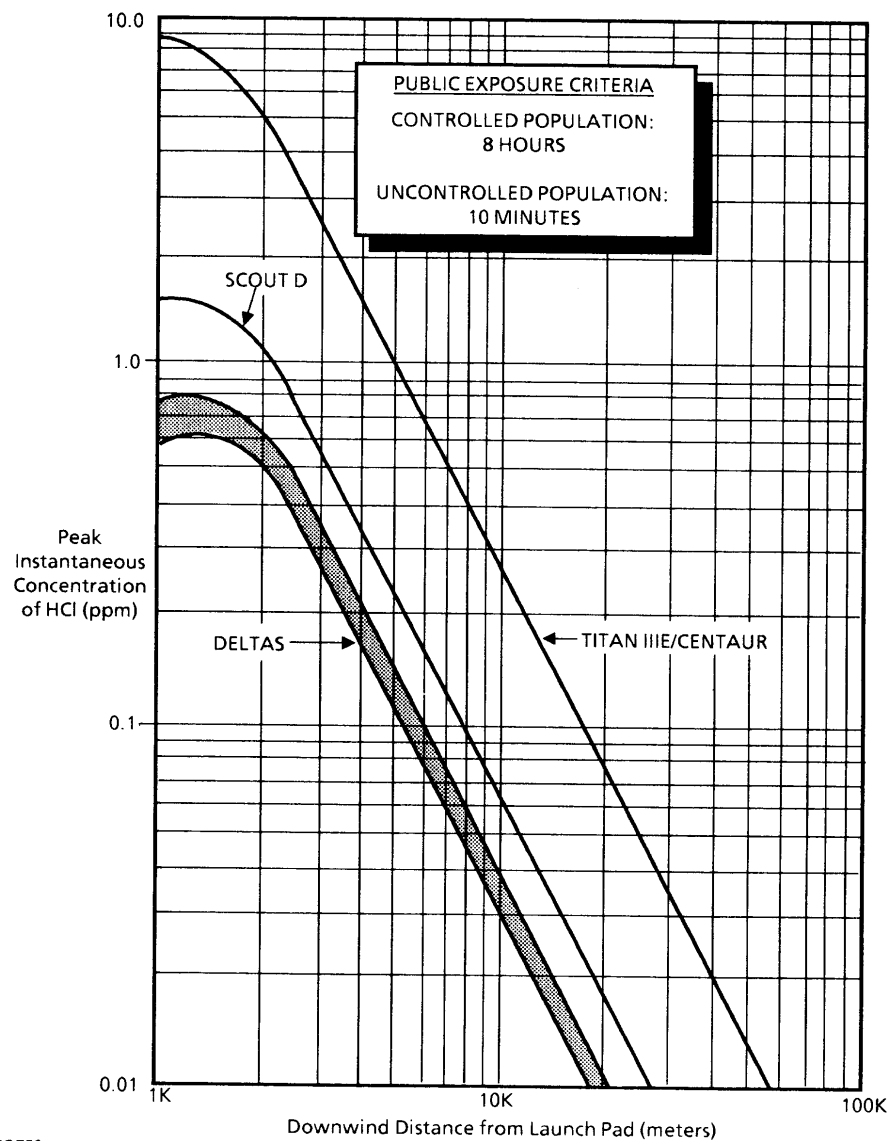
f) There are no officially recognized standards.

f) There are no officially accepted criteria for short-term exposure of uncontrolled populations to nitrogen oxides. The criteria given here have been proposed by a responsible organization after careful evaluation of the available data.

g) Ordinarily set equal to the 8 hour industrial TLV. The criteria given here have been proposed by a responsible organization after careful study. The criteria are not intended to be applied to populations of nitrogen oxides.

h) Ordinarily set equal to the 8 hour industrial TLV: i.e., 1/48 of the acceptable industrial dose. Based on hydrolysis to HCl. In subsequent discussion, AIC_h is considered only in terms of AIC_h.

based on hydrolysis to HCl. In subsequent discussion, AlCl_3 is considered only in terms of its contribution to overall HCl levels.



NOTES:

1. The concentrations for the 3, 6 & 9 Castor Deltas fall within the shaded area.
2. To convert meters to statute miles, multiply by 6.2×10^{-4} .

FIGURE 5-9. ESTIMATED PEAK HCl CONCENTRATIONS DOWNWIND OF LAUNCHES (SEA BREEZE METEOROLOGICAL CONDITIONS) Ref. 14

Depending on their chemical properties (see Appendix B), accidentally released vapors may only be flammable (e.g., hydrogen) or also toxic (e.g., hydrazine and nitrogen tetroxide). The Threshold Limit Values (TLV) for exposure to various toxic propellants or their combustion products, shown in Table 5-7 and Appendix B, are on the order of 0.1-100 ppm, while typical flammability limits are on the order of 1-10% (i.e., 10,000-100,000 ppm). Because the minimum vapor concentrations with toxic impacts are much below those required to sustain a flame, the potential size of a toxic cloud is much greater than that of a flammable cloud. Accordingly, for equal amounts of released propellants, the potential for toxic impacts is of greater concern than for fire damage.

5.6 OFF-RANGE IMPACTS ASSOCIATED WITH ELV OPERATIONS

This section presents a summary discussion of the potential off-range impacts associated with ELV operations (See Table 5-8). Potential ELV hazards were discussed in this chapter with no explicit mention of the associated probabilities. However, each hazard is tied to a particular probability value -- that of the occurrence of the enabling conditions. This fact should be remembered in assessing the significance of potential off-range impacts. The subject of assessing impacts from the perspective of both their magnitude and probability is referred to as Risk Analysis, and it, along with the various methods used to quantify risks, is discussed in detail in Chs. 8 and 9, Vol. 3.

Illustrative examples of the application of Failure Analysis methods to space systems are given in Ch. 9, Vol 3. They are typically focused on a specific phase of launch operations and are rarely integrated, as is attempted (qualitatively) below.

Examples of the results from such a preliminary hazard analysis are given in Table 5-8 for the main phases of ELV operations: pre-launch, launch and pre-orbital. As usually done, the failure types are classified in a manner compatible with the availability of data. For example, in Table 5-8, all failures leading to vehicle break up in flight, are lumped into one category for which a failure rate may be estimated based on historical data for each ELV.

Hazard Analysis is then used to analyze the consequences of the types of accidents identified in Failure Analysis. These consequences include explosion, fire, toxic vapor clouds and inert debris. The principles of physics and chemistry are used, along with data from historical experience, testing and engineering judgment, to describe the hazards and potential impact severity. For example, the strength of an explosion or fire may be described and associated with potential damages

TABLE 5-8 ADVERSE OFF-RANGE ACCIDENT IMPACTS FOR VARIOUS PHASES OF SPACE LAUNCH OPERATIONS

Phase/Time, sec. after lift-off	Selected ELV Failure Types	Probability of Failures	Potential Off-Range Impacts*			
			Explosion	Fire	Toxicity@	Inert Debris
Pre-launch						
	Storage tanks	Improbable	(a)	(a)	(b)	N/A
	Small Leaks	Occasional	(a)	(a)	(a)	N/A
Launch						
0-12	Fallback/Tipover	0.04 - 0.1 (j)	(c)	(d)	(b)	(d)
25-70	Thrust/Guidance Failure and Break-up in flight	0.04 - 0.1 (j)	(e,f)	(e,f)	(e,f)	$E_c = 2.3 \times 10^{-8}$ with FTS (Near ESMC, h)
70-400	Thrust/Guidance Failure and Break-up in flight	0.04 - 0.1 (j)	(g)	(g)	(g)	$E_c = 4.0 \times 10^{-3}$ without FTS (near ESMC, i)
Pre-orbital						
	Thrust/Guidance Failure and Break-up in flight		(g)	(g)	(g)	$E_c = 8.0 \times 10^{-7}$ regardless of FTS (Over Africa, l)

NOTES:

* Risk can be described by number of casualties (or dollar loss) weighted by its probability, or by an expected casualty E_c . The probability depends on the failure mode and accident rates and other accident circumstances.

@ For hypergolic propellants only

- Large separation distances in Range siting and propellant storage preclude such hazards.
- Possible with very large releases and adverse meteorological conditions.
- Depends significantly on yield which in turn depends on accident scenario; window breakage is possible.
- No likely impacts off-range.
- Remaining fuel and hazard decrease rapidly as time elapses after launch.
- Hazard depends on number of fragments, size and impact points.
- Remaining propellant (if any) is likely to dissipate in flight.
- E_c = expected casualties per launch Ref. 22
- E_c = expected casualties per launch (see Sec. 9.1)
- Based on historical failure rates of all ELVs as given in Ch. 3.
- E_c from Table 9-1, Ch. 9.

N/A = Not Applicable

(by overpressure or heat) to people and/or property. Estimates of the magnitude of the potential damage may be expressed in terms of an impact area (or footprint) surrounding the location of the accident.

To do so, a range of possible accident circumstances have to be specified to allow a quantitative estimation. A further break down of the hazards in various ways may be needed to make the analysis tractable. For example, in Table 5-8, the hazards are divided into those (explosion, fireball and toxic releases) that may occur while the vehicle is in flight, versus those occurring when the vehicle or its fragments impact the ground. The breakdown of consequences in Table 5-8 varies with time during the launch phase. As time elapses after liftoff, the quantities of propellants on-board will decrease, thereby affecting their potential hazards. This was discussed in detail in Section 5.2.4 for explosion hazards.

Risk Analysis is finally used to describe (for a particular activity) both the probabilities of accidents and the possible damages or losses associated with them, accounting for uncertainties in the occurrence of the accidents and in the circumstances surrounding them. For example, there are uncertainties as to what accident is likely to occur at a particular location and how many people would be present at that location at the time of the accident. A set of circumstances is defined (scenario) and their probability is estimated. For each set, the results of the Failure Analysis (frequency of an accident) and Hazard Analysis (area of damage) are combined to estimate an expected damage (e.g., a number of people affected with a particular frequency per year or per event). The overall outcome of the analysis is a probability distribution function (PDF) for the potential damages that can be associated with a particular hazardous activity. An expected value for potential damage (e.g., casualty expectation, E_c) is often calculated from that probability distribution.

Such expected casualty values have been estimated in an approximate manner for ELV-type vehicles, but only for a few specific scenarios involving inert debris hazards as shown in Table 5-8, namely:

- inert debris risks during the first 10-70 sec of launch, with and without a Flight Termination System.⁽²²⁾
- inert debris risks during pre-orbital operation, with and without a Flight Termination System.

In Table 5-7, note that for the scenarios involving explosion, fire and toxic hazards, only a qualitative description of the potential off-range impacts is given because either their probabilities or magnitudes have not been quantified. These descriptions are given as footnotes in Table 5-8, to summarize key considerations in understanding these impacts and of their determining factors.

5.7 PERSPECTIVES ON THE MAGNITUDE OF THE HAZARDS ASSOCIATED WITH ELV PROPELLANTS

In the previous sections, the major hazards associated with ELV propellants were discussed. There are a number of hazards (explosions, debris, fires, toxic vapor clouds) each of which depend on a number of parameters such as propellant properties, quantity, mode of release, etc. Clearly, these hazards are very complex and multi-dimensional. In this section, a few reference points are provided to place these hazards in perspective compared to more familiar hazards. Only a partial perspective is provided because:

- (a) the focus here is on the magnitudes of these hazards and not on their probabilities or likelihood of occurrence. This is addressed in Chs. 9, 10, Vol. 3, where a more complete discussion of public risk perspectives is provided.
- (b) the comparison with other hazards is presented in a very simplified fashion, focusing only on selected dimensions of the hazards.

In simple terms, concern with ELV propellant hazards can be attributed to the following factors:

- (1) rocket propellants are highly energetic fuels and most are inherently hazardous;
- (2) large quantities of propellants are involved in space launch operations; and
- (3) launch operations are inherently complex and have many potential failure modes.

The following discussion places these concerns in their proper perspective.

First, propellants such as liquid hydrogen, liquid oxygen and RP-1 have been used extensively in the chemical industry. They have been processed, transported and stored for several decades with a remarkable safety record. Also, the chemical industry uses (on a daily basis) chemicals which are even more hazardous than ELV propellants, such as acetylene and ethylene oxide (which are

extremely explosive) and hydrogen chloride and hydrogen cyanide (which are extremely toxic).

Selected key properties which affect the hazard potential of such chemicals are listed in Appendix B and in Table 5-9. Note that the range of propellant properties are sometimes exceeded by other chemicals. For example, the flammability limits of acetylene and ethylene oxide are wider than those of hydrogen. In addition, these two chemicals can react autocatalytically without the need for an oxidizer, if initiated by heat, pressure or shock. On the other hand, hydrogen requires oxygen to react. Generally, the broader the flammability range, the easier it is to create a fire or an explosion. Thus, these two chemicals are more likely to ignite than hydrogen.

Second, the quantities of chemicals used in industry are often greater than those of propellants in ELV operations. This is illustrated in Table 5-10 which provides data for various space vehicles and for the storage and transportation of fairly common fuels such as LNG, LPG and gasoline. For each case, the table gives the total weight, heat of combustion per unit mass, and the total chemical energy. It also would have been desirable to provide the explosive (TNT) yield for each case. However, this would require the definition of a pertinent accident scenario for each (as was done in Sec. 5.2.4) and the estimation of a reasonable yield.

In view of the lack of such data, instead the total chemical energy is used as a rough indication of the magnitude of the potential hazard which is reasonable for propellants and fuels. In terms of total chemical energy alone, three typical launch vehicles are approximately:

- equivalent in order of magnitude to a gasoline truck or a rail tank car of LPG.
- one order of magnitude smaller than a pressurized LPG sphere.
- two orders of magnitude smaller than standard cryogenic tanks of LNG and LPG.
- three orders of magnitude smaller than an LNG ship.

Third, although ELV launch operations are inherently more intricate and complex than conventional chemical and transport operations, the safety precautions for ELV operations are far greater than those for other more common activities. For example, launch sites are separated significantly from population centers while chemical plants and fuel tank farms are located within cities.

TABLE 5-9. SELECTED PROPERTIES AFFECTING THE HAZARDOUS BEHAVIORS OF LIQUID PROPELLANTS AND CHEMICALS

Property	LH ₂	LO ₂	RP-1*	Hydrazine	N ₂ O ₄	LPG**	LNG†	Gasoline	Acetylene	Hydrogen Cyanide	Ethylene Oxide
Boiling Point or Distillation Range (at 1 atmosphere), °K	20.3	90	440-539	387	294.3	227	111.6	310-478	189	299	284
Vapor Pressure, at 311° K, kPa	gas	gas	1.4	5	273	gas	gas	46	gas		233
Flash point at 1 atmosphere, ° K	gas	NA	~330	310-525	NA	gas	gas	~230	gas		
Net heat of combustion, kJ/kg	119,900	NA	43,200	49,300	NA	46,400	50,000	44,500	48,200	13,100	27,700
	51,630	NA	18,600	21,300	NA	20,000	21,500	19,200	20,800	5,600	12,000
Flammability limits in air (volume %)											
Lower	4	NA	0.6	4.7	NA	2.2	5.3	1.7	2.5		2
Upper	75	NA	4.7	100	NA	9.6	15	7.6	81		100
Autoignition temperature at 1 atm, ° K	858	NA	511	497-543	NA	766-877	813	501-744	578		
Minimum Electric Spark Ignition Energy, mJ	0.02	NA	0.2			0.29	0.29	0.24			
Approximate laminar flame speed, m/s	2.7-3.3	NA	0.3-0.6				0.37-0.45		0.37-0.43		
Comments		Intensifies combustion with most materials			Very strong oxidizer				Unstable under heat or shock	Extremely toxic	Unstable in presence of heat and may undergo autocatalytic polymerization and decomposition

Source: Data are taken from a number of handbooks and reports and are approximate.

Notes:

NA = Not applicable because it is an oxidizer, not a fuel

* taken as mainly kerosene

** taken as mainly propane

+ taken as mainly methane

TABLE 5-10. COMPARISON OF CHEMICAL ENERGY CONTENTS OF SPACE VEHICLES AND OTHER INDUSTRIAL OPERATIONS

<u>System</u>	<u>Propellant/fuel</u>	<u>Weight Klb</u>	<u>Heat of Combustion Btu/lb*</u>	<u>Total Chemical Energy Btu</u>
Atlas	RP-1/LO ₂	303	5,850	1.8×10^9
Centaur	LH ₂ /LO ₂	30.7	7,200	0.2×10^9
				2×10^9
Delta				
Booster	Solid (Castor (IV))	186	1,950**	0.36×10^9
Stage 1	RP-1/LO ₂	179	5,850	1.0×10^9
Stage 2	Aerozine-50/N ₂ O ₄	13	7,200	0.09×10^9
Stage 3	Solid	2.3	1,950**	0.004×10^9
				1.5×10^9
Titan III				
Stage 0	Solid (UTP-300 1B)	464	1,950**	0.9×10^9
Stage 1	Aerozine-50/N ₂ O ₄	294	2,000	0.59×10^9
Stage 2	Aerozine-50/N ₂ O ₄	69	2,000	0.14×10^9
Transtage	Aerozine-50/N ₂ O ₄	9	2,000	0.02×10^9
				1.7×10^9
LNG tanker (Cryogenic)				
1 tank: 25,000 m ³	LNG	23,000	21,500	500×10^9
entire ship: 5 tanks	LNG	115,000	21,500	$2,500 \times 10^9$
Cryogenic Storage Tank (100,000 bbl)	LPG	20,000	20,000	400×10^9
Pressurized Spheres (1,200 m ³)	Propane	950	20,000	19×10^9
Jumbo jet fully loaded (50,000 gallons)	Jet A	390	18,600	7.3×10^9
Rail tank car	Propane	139	20,000	2.8×10^9
Tank Trucks (10,000-20,000 gal.)	Gasoline	60-120	18,000	$1.1 \text{ to } 2.2 \times 10^9$

* The heat of combustion is given in Btu per lb of fuel/oxidizer mixtures for propellants and per lb of fuel for non-space applications.

** Assumed to be same as TNT.

An additional perspective on the magnitude of the hazards of ELV propellants relative to other fuels and chemicals can be obtained by comparing their respective past accident data. This is presented below for explosion accidents.

Data summarized in Table 5-11 involve major chemical process and transportation activities where the explosive yield was 40,000 pounds of TNT or greater. The table provides a brief description of each accident, identifies the chemical involved, the approximate quantity released (pounds) and the TNT equivalent weight (reported by the accident investigators based on the observed damage at the location of the accident). The TNT equivalent weights ranged from 40,000 to 125,000 pounds, which is roughly the same order of magnitude as that estimated conservatively for worst case propellant accidents in Table 5-3.

Unfortunately, similar historical data on space vehicle accidents may be restricted or classified and are not readily available in the open literature. The data found in the open literature are shown in Table 5-12 for large SRM explosions. No comparable data were found for liquid propellants. The reported TNT equivalent weights range from 9 to 42,000 pounds, a range lower than yields from industrial/transportation accidents and lower than the estimates for worst case propellant accidents in Table 5-3.

Although the historical data and comparisons presented above are limited in scope and depth, they still suggest that the hazards anticipated from ELV propellants can be considered to be qualitatively similar in type and magnitude to those associated with comparable chemicals and fuels commonly used in chemical processing and transportation activities.

TABLE 5-11. EXAMPLE OF MAJOR ACCIDENTAL EXPLOSIONS OF FUELS AND CHEMICALS AND THEIR TNT EQUIVALENT WEIGHTS (ESTIMATED FROM ACTUAL DAMAGES) (Ref. 20)

<u>Date</u>	<u>Location</u>	<u>Chemical</u>	<u>Quantity Released klb</u>	<u>TNT Equivalent Weight klb</u>	<u>Accident Description</u>
<u>CHEMICAL PROCESS INDUSTRY</u>					
1970	N.J.	Heavy Hydro-carbon and hydrogen	251	110	Failure of high pressure reactor due to localized overheating. Blast was highly directional. Peripheral damage was used to indicate yield.
12/9/70	Port Hudson, MO	Propane	150	110	Spill from a pipeline rupture produced cloud 460 m long, and 3-6 m high.
1/20/68	Parnis, Holland	Light Hydrocarbons	110-220	44	Breaking of water-oil emulsion in stop oil tank caused cloud.
6/1/74	Flixborough, England	Cyclohexane	79	40	Poorly installed 500 cm pipe failed. Ignition in 25-35 sec.
4/17/62	Doe Run, KY	Ethylene Oxide	48	40	Tank containing ethylene oxide became contaminated with ammonia. Tank ruptured, dispersed ethylene oxide into air. Ignition was immediate.
<u>TRANSPORTATION</u>					
9/21/74	Houston, TX	Butadiene	176	44-125	Accident in rail yard punctured rail tank car. Amount of spill in 2-3 minutes not known. Ignited by locomotive 180 m away. Estimate 14-21 kPa over-pressure at 300 m from point of rupture.
7/19/74	Decatur, IL	Propane	139	44-88	Accident created 56 cm x 65 cm hole in end of rail car, releasing contents.

TABLE 5-12. HISTORY OF LARGE SRM EXPLOSIONS AND THEIR TNT EQUIVALENT WEIGHTS

MOTOR TYPE	SIZE		PROPELLANT TYPE	HAZ. CLASS	INIT. WT. klb.	TNT EQUIV WT. klb.	INCIDENT DESCRIPTION	IMPACT	
	LGTH. ft.	DIAM. ft.						SPEED ft/s	SURFACE
TRIDENT F/S	15.5	6.2	CXDB	1.1	42	42 +		<800	WATER
STS Seg.		13.0	TP-H1123	1.3	280	28			
TRIDENT S/S	8.3	6.2	CXDB	1.1	19	19 +		<800	WATER
M ² Stage II	13.5	4.3	PBAA	1.3	10.5	10.5		>600	SAND
M ² Stage I	24.5	5.4	PBAA	1.3	45.8	6.4-8.2		380-490	SAND
TITAN III Seg.	12.0	10.0	PBAA	1.3	82	6.6-11.5		670	CONCRT.
M ² Stage III	5.2	3.1	DDP77	1.1	3.7	3.7 +		<600	SAND
POLARIS F/S	15.1	4.5	ANP2655	1.3	15.2	2.6		>490	SAND
POLARIS S/S	7.0	4.5	ANP2655	1.3	7.3	1.81		>575	SAND
M ² Stage II	13.5	4.3	PBAA	1.3	10.5	0.105		40	STEEL
MX Stage I		7.7	HTPB	1.3	95.1	0.06	HOT DESTRUCT, LSC = 325 g/ft		
MX Stage III		7.7	HTPB	1.3	15.5	0.009	HOT DESTRUCT, LSC = 40 g/ft		

Source: Ref. 7

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